# Evidence of intrinsic charm in the proton

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# Outline

- Theory background
- Methodology
- Results
- Further developments
- Summary and Outlook

# Outline

**Theory background**

Methodology

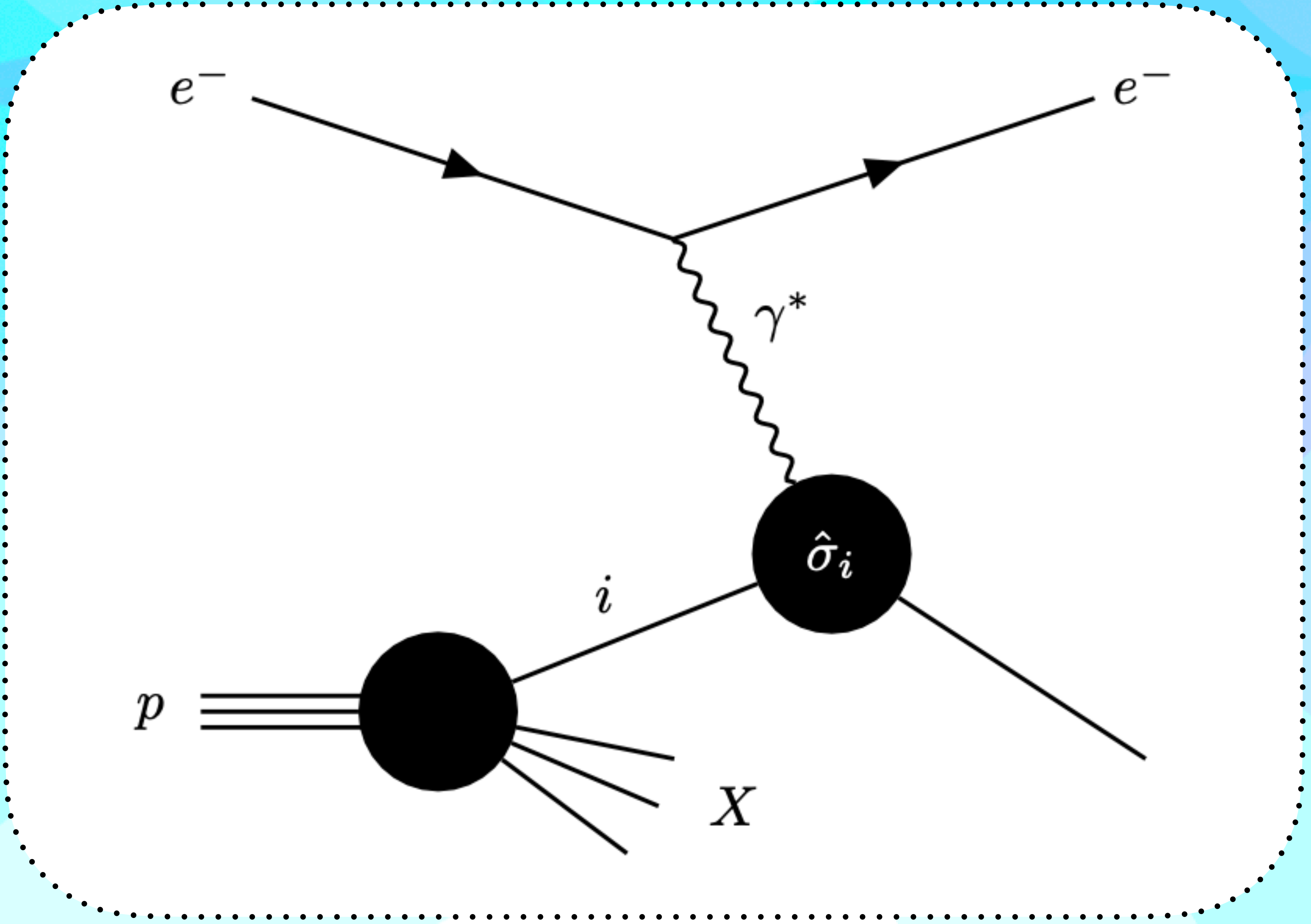
Results

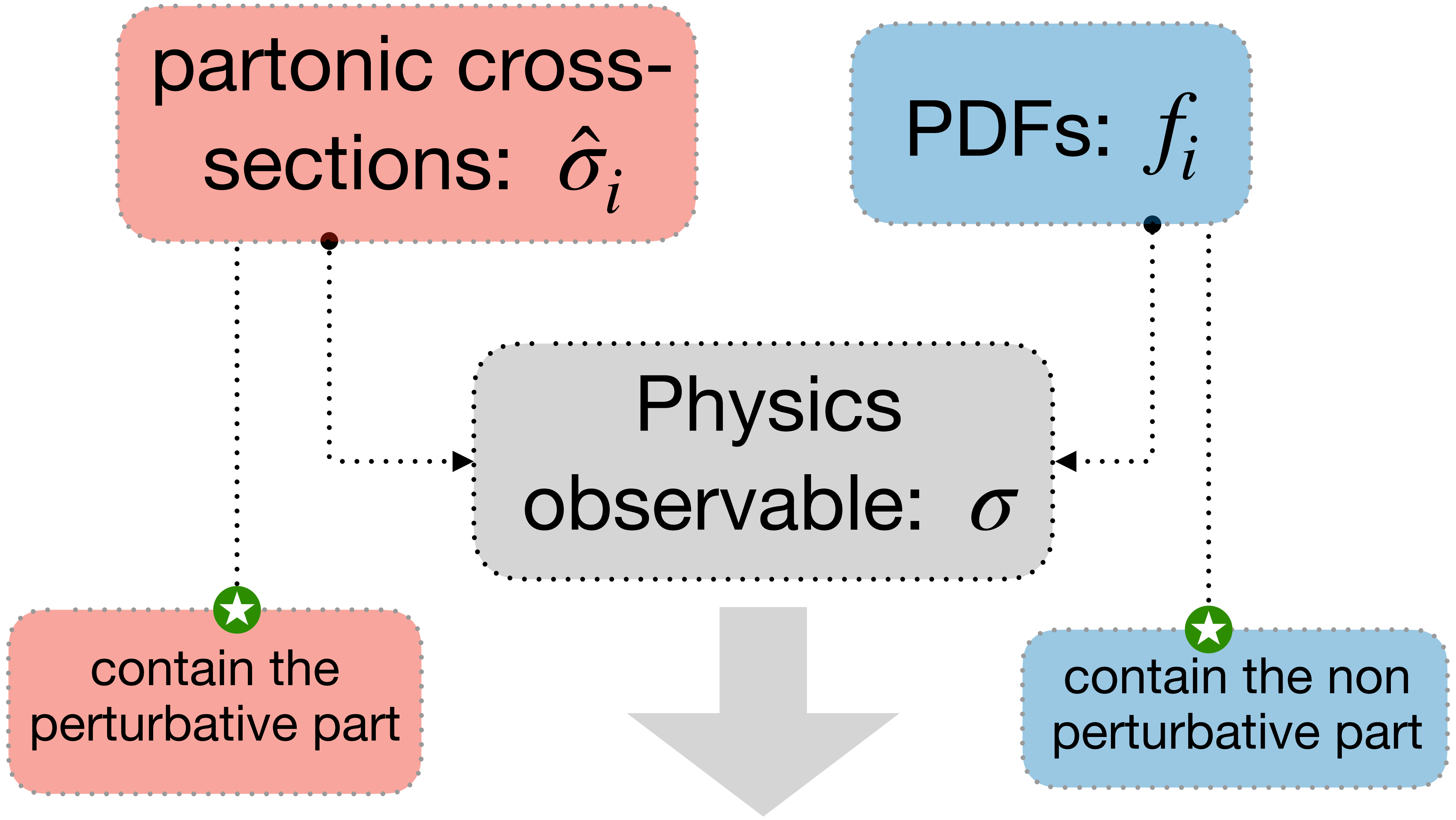
Further developments

Summary and Outlook

- How do we compute observables in HEP?
- What are the PDFs?

Deep inelastic scattering (DIS)



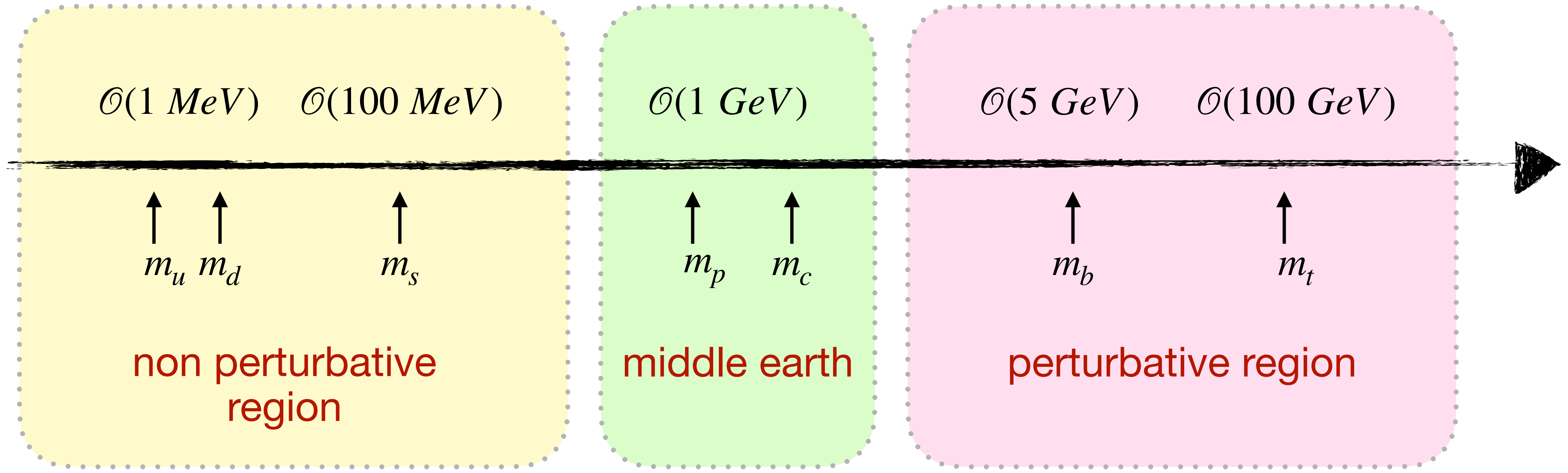




## Factorization theorem

$$\sigma = \sum_i \hat{\sigma}_i \otimes f_i + \mathcal{O}(\Lambda^2/Q^2)$$

- Which quark does have a PDF?
- What do we mean with intrinsic charm?

Quark masses:




$m_u, m_d, m_s \ll m_p$ their PDF has a non perturbative origin

$m_b, m_t \gg m_p$ they are originated perturbatively by the gluon splitting in quark-antiquark

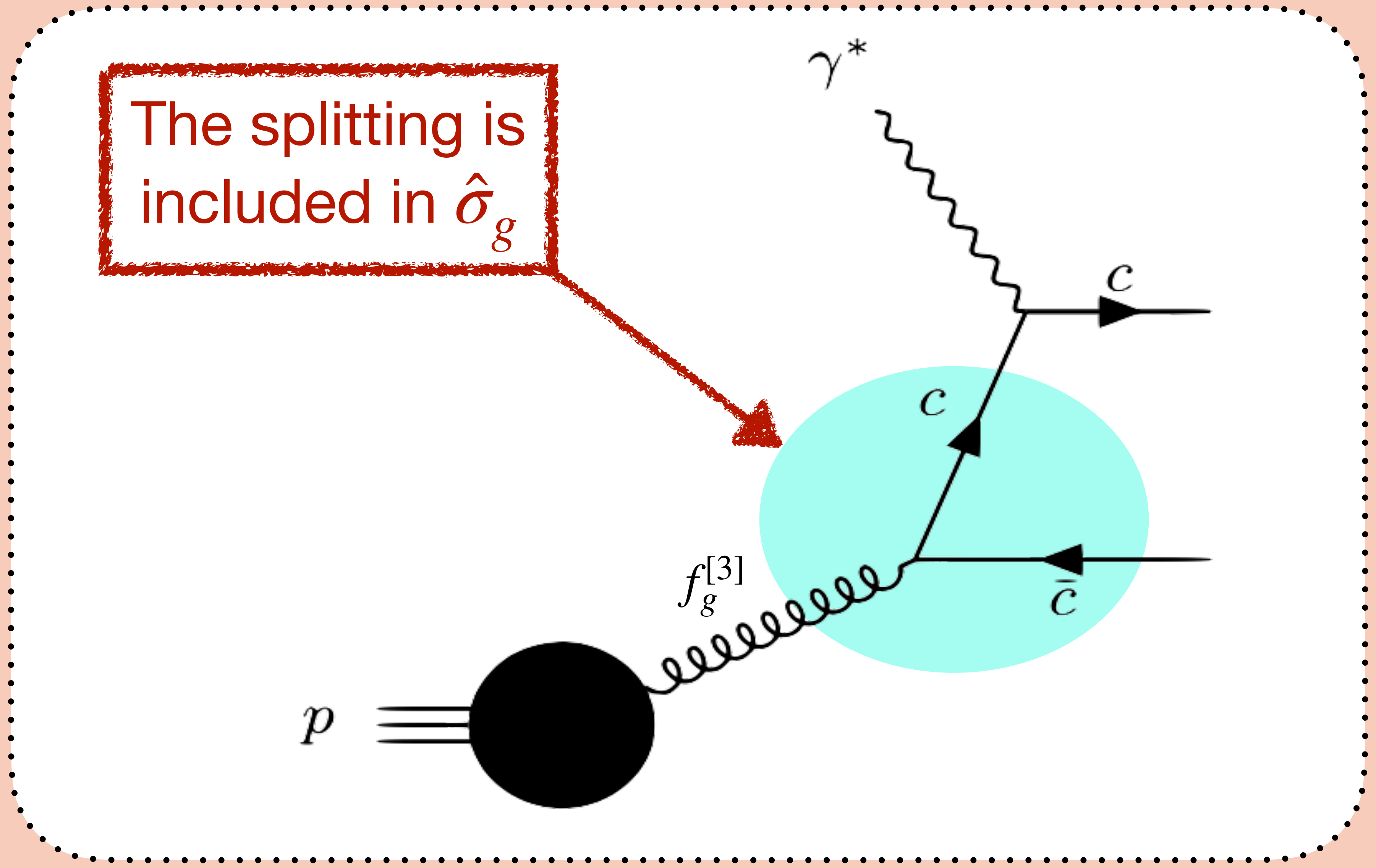
$m_c \sim m_p$ we cannot neglect a charm intrinsic component

What do we mean with intrinsic? Is there also a non intrinsic charm PDF?

# Observables can be computed in different **schemes**:

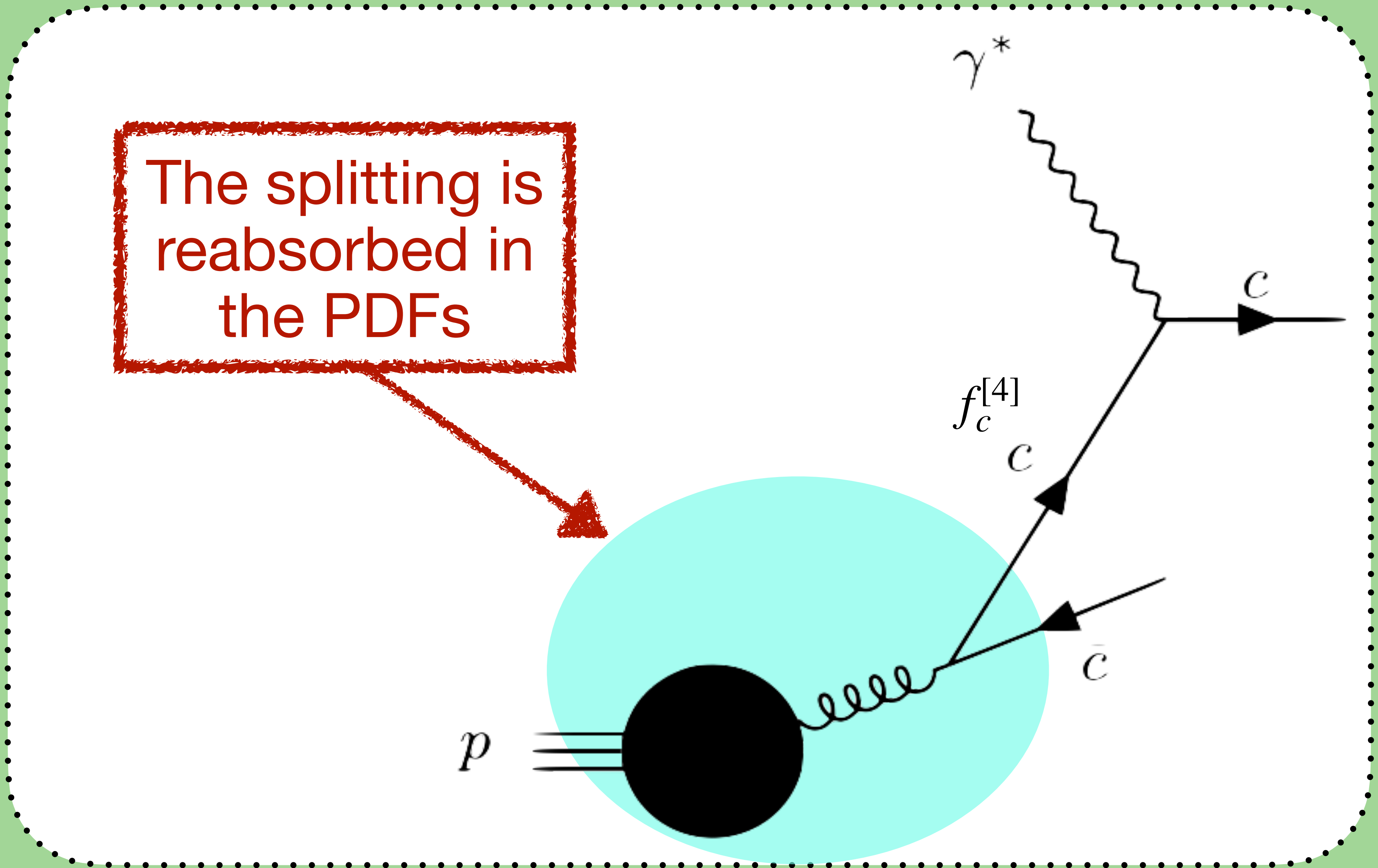
## 3 Flavor scheme (3FS)

- 3 light flavors $\Longrightarrow$ only $u, d, s, g$ evolve with DGLAP
- $\hat{\sigma}_i$ contain the charm mass dependence




## 4 Flavor scheme (4FS)

- Charm is massless $\Longrightarrow$ it evolves with DGLAP
- The charm splittings are reabsorbed in the PDFs




3FS — $\mu_c \sim \mathcal{O}(m_c)$ — 4FS — $\mu_b \sim \mathcal{O}(m_b)$ — 5FS — $\mu_t \sim \mathcal{O}(m_t)$

Putting $m_c = 0$ above $\mu_c$ would be a rough approximation. Things are more complicated than that! (backup)

- How do we relate PDFs in different flavor schemes?
- Which are the different components of the charm PDF?

$$f_i^{[4]}(\mu_c) = \sum_{j=g,q,\bar{q},c,\bar{c}} A_{ij}\left(\frac{m_c^2}{\mu_c^2}\right) \otimes f_j^{[3]}(\mu_c^2) \quad i = g, q, \bar{q}, c, \bar{c}$$

$A_{ij}$ are the matching conditions: almost fully known up to $\mathcal{O}(\alpha_s^3)$

$$A_{ij} = \begin{cases} 1 + \mathcal{O}(\alpha_s) & i = j \\ \mathcal{O}(\alpha_s) & i \neq j \end{cases}$$

$$f_c^{[4]}(\mu_c) = \left(1 + \alpha_s A_{cc}^{(1)}\right) f^{[3]}(\mu_c) + \alpha_s \sum_{j=g,q,\bar{q}} A_{cj}^{(1)} \otimes f_j^{[3]}(\mu_c^2) + \mathcal{O}(\alpha_s^2)$$

**Intrinsic part:** not present with zero intrinsic charm

**Perturbative part:** present also with zero intrinsic charm

The intrinsic charm is the charm PDF in the 3FS, i.e. below $\mu_c$

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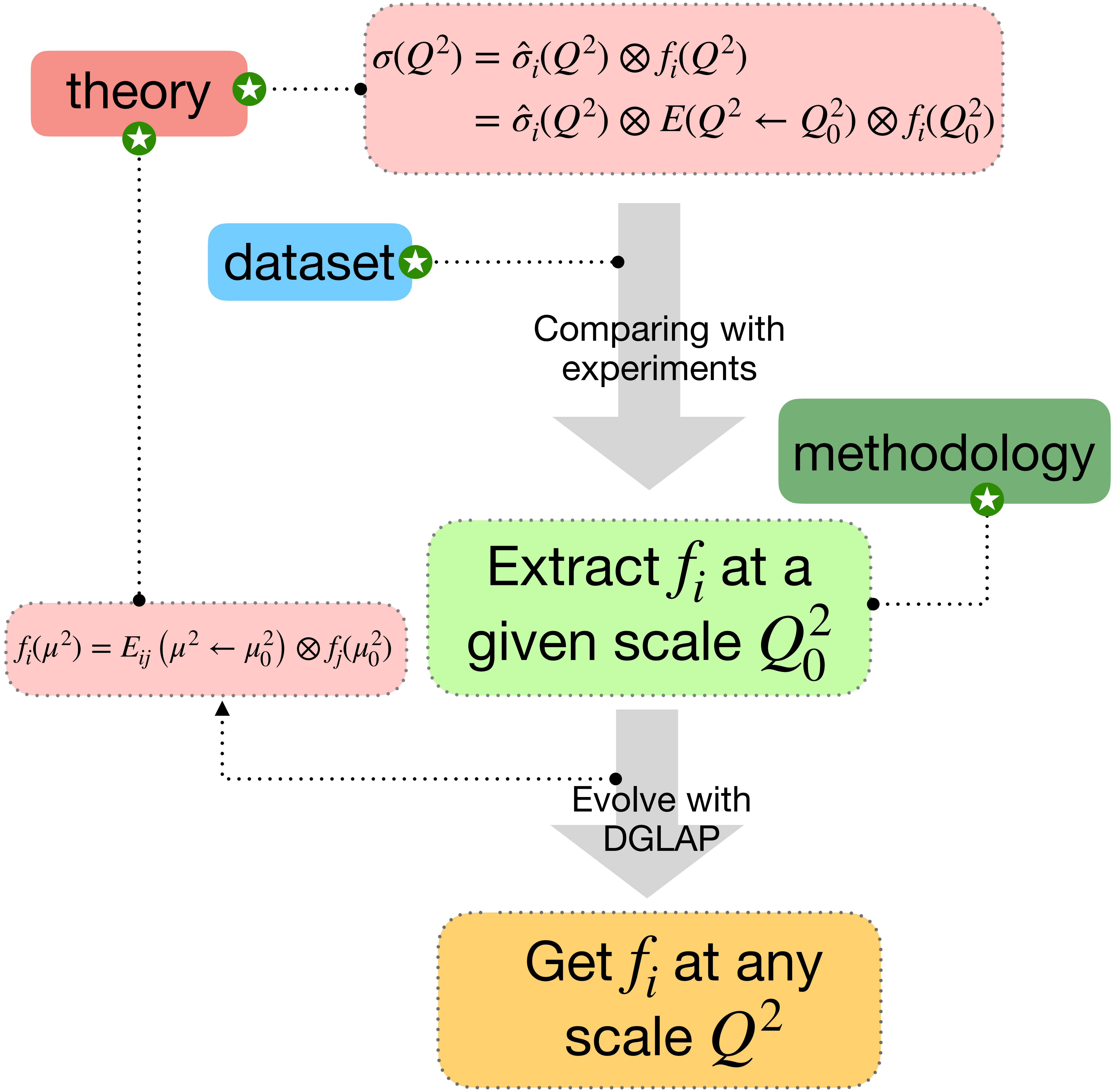
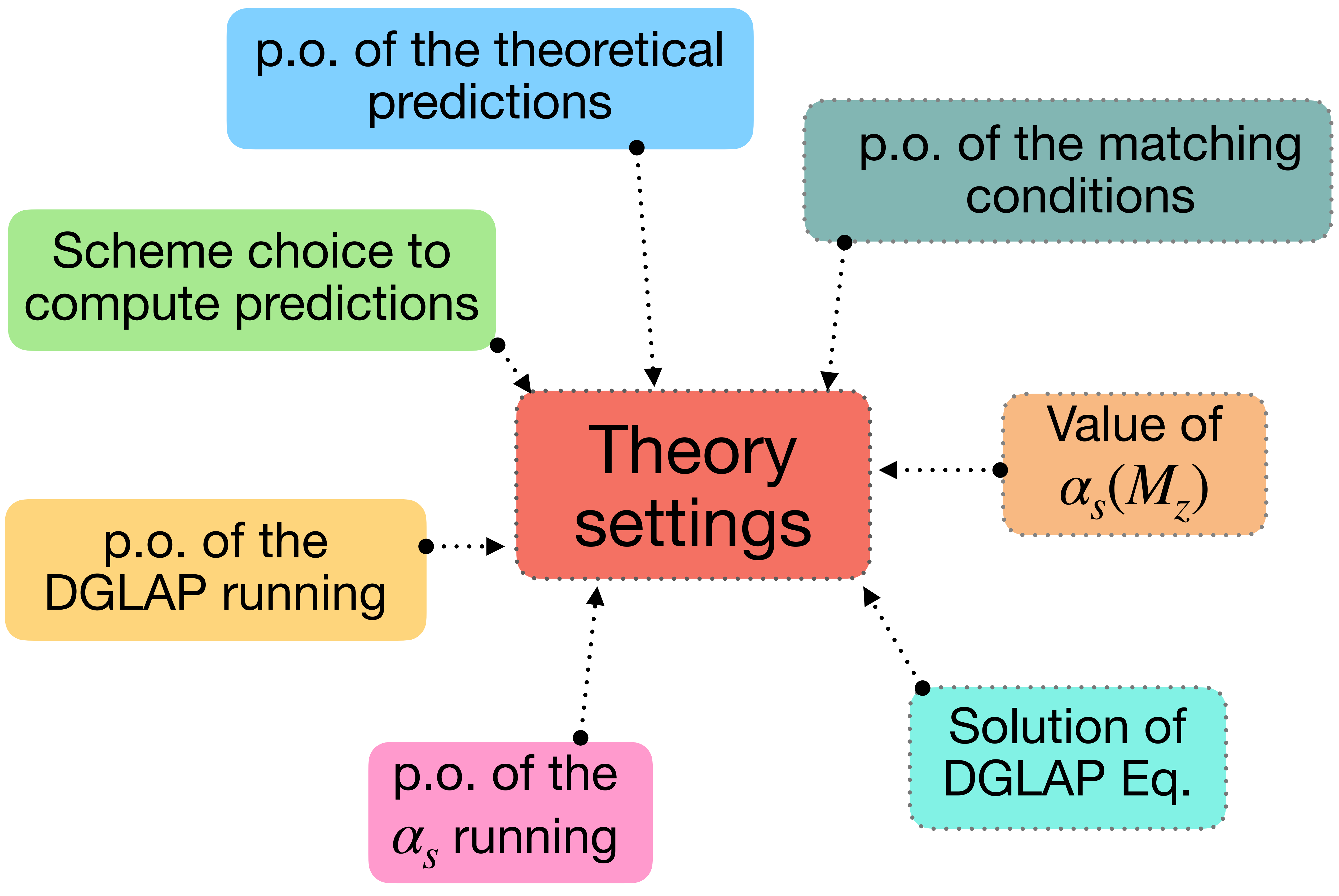
- How are the PDFs fitted?
- Which ingredients are required for a PDFs fit?



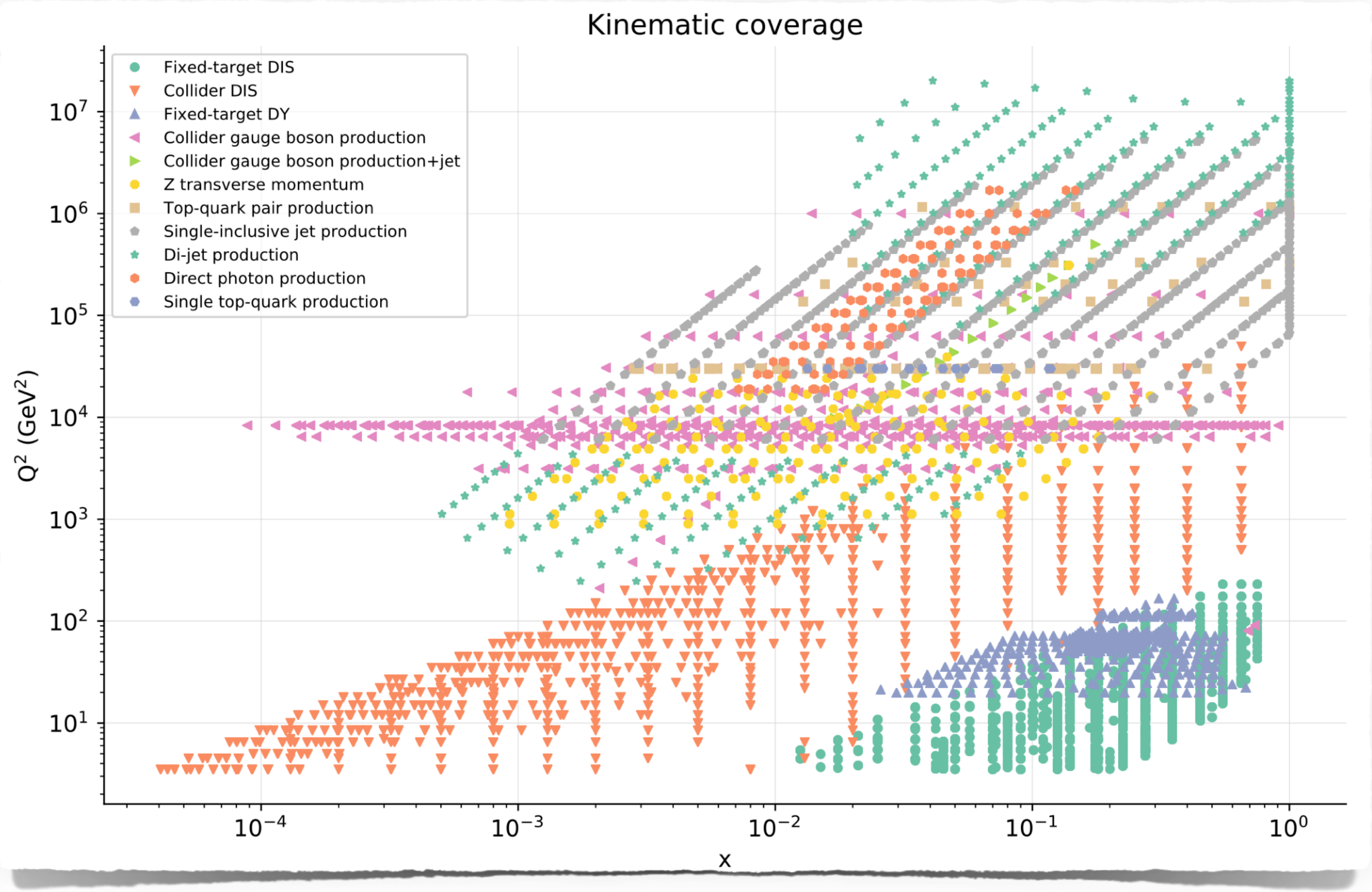
- Theory
- What defines the theory of a fit?

**p.o.= perturbative order**




In this analysis we used a NNLO theory !

- Dataset
- Which data points are included in the fit?




4618 data points from different processes

- Methodology
- How are the PDFs extracted?

PDFs are parametrized through neural networks

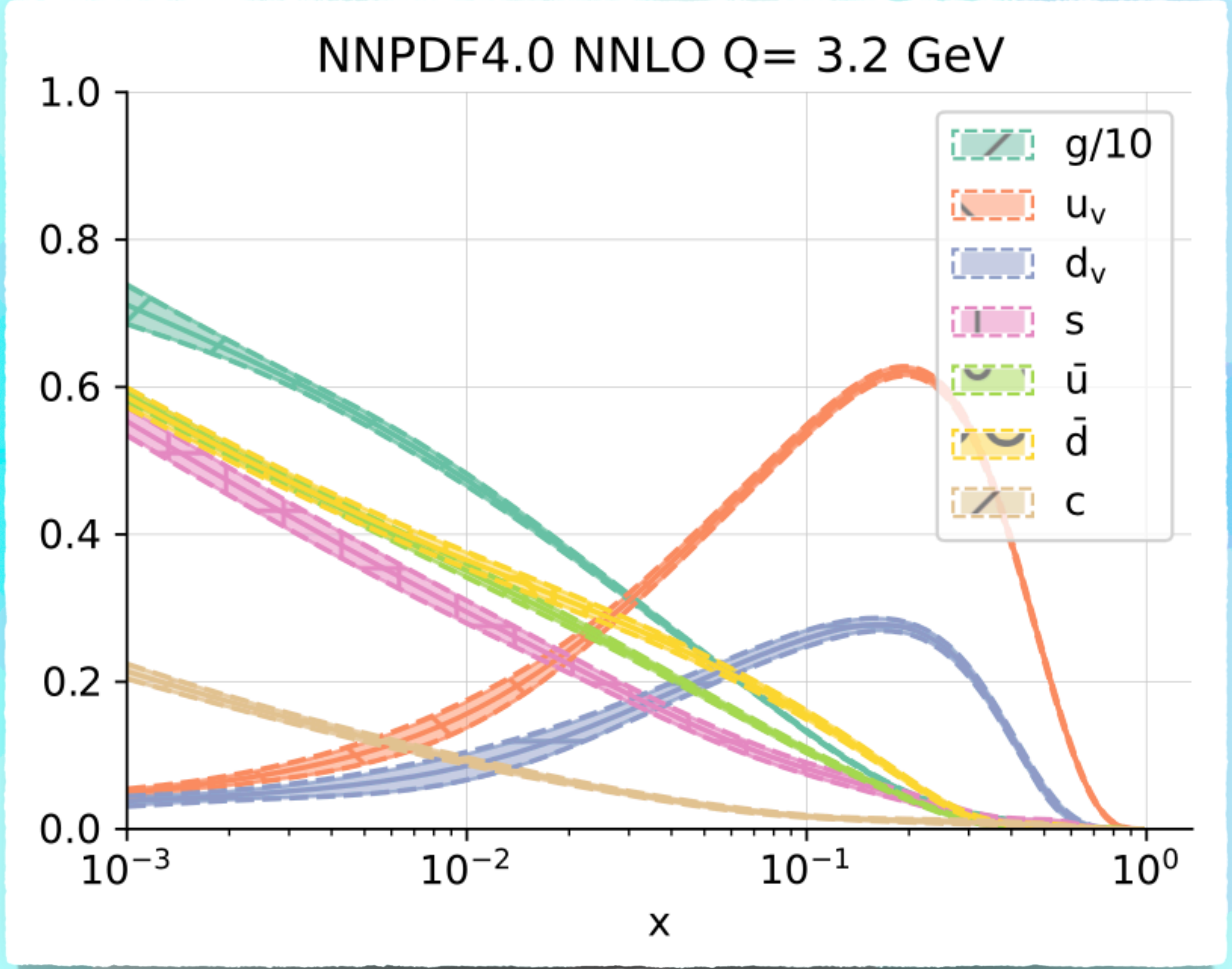
8 PDFs to parametrize: $g,\ u, \bar{u}, d, \bar{d}, s, \bar{s}, c$ we imposed $c = \bar{c}$

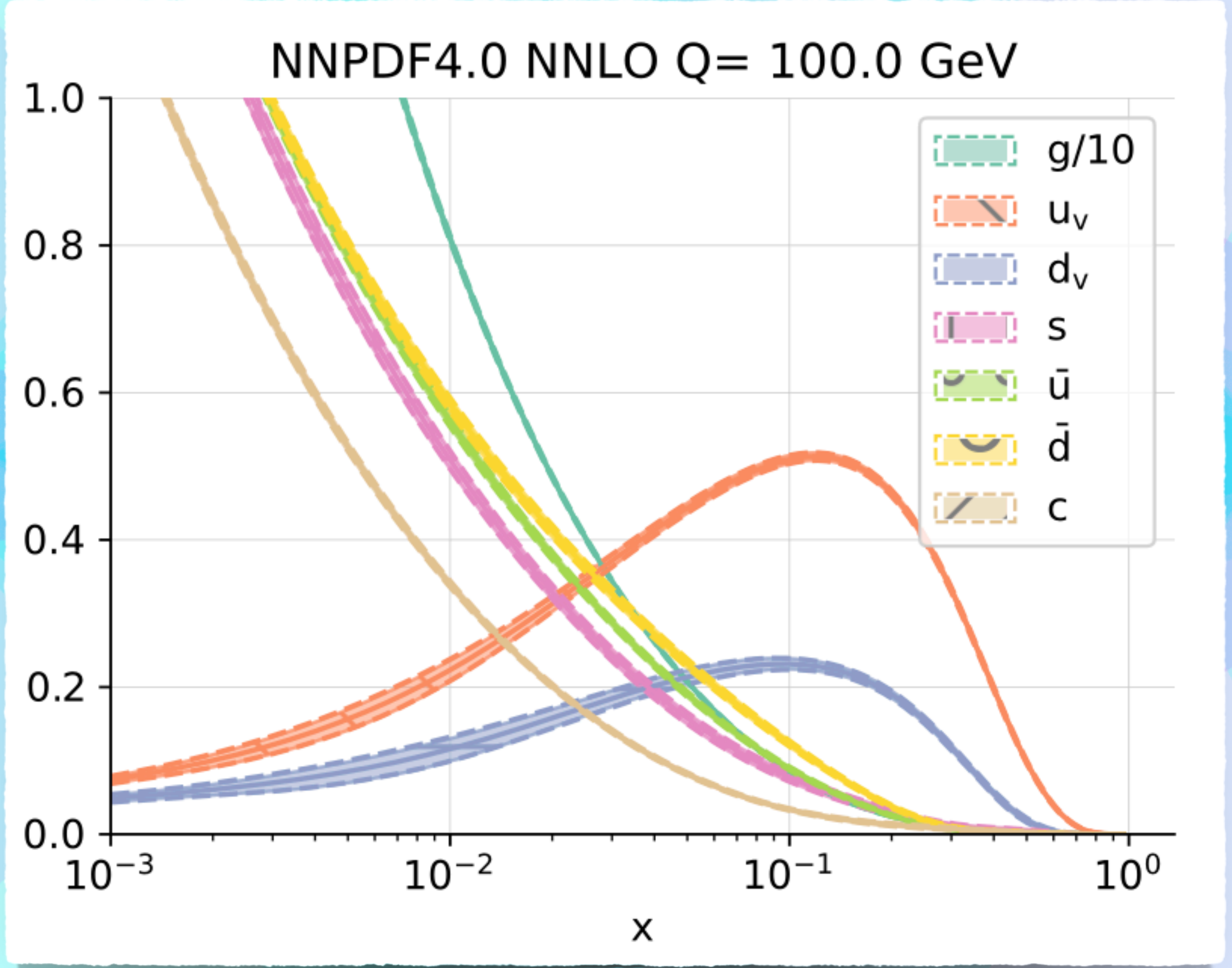
$$xf_k(x, Q_0^2; \theta) = A_k x^{1-\alpha_k} x^{\beta_k} \mathrm{NN}_k(x, \theta)$$

$\theta$: parameters of the neural networks

Uncertainties are generated through Monte Carlo replicas

# Results of the fit



- How did we determine the intrinsic charm?

Step 1: perform a fit with $Q_0 = 1.65 > \mu_c = m_c$

Gives $f_i^{[4]}(Q_0^2)$

Step 2: evolve $f_i^{[4]}(Q_0^2)$ back to $\mu_c$

$$f_i^{[4]}(\mu_c^2) = E_{ik}(\mu_c^2 \leftarrow Q_0^2) \otimes f_k^{[4]}(Q_0^2)$$

Step 3: obtain charm PDF in 3FS

$$f_c^{[3]}(\mu_c^2) = A_{ck}^{-1}\left(m_c^2/\mu_c^2\right) \otimes f_k^{[4]}(\mu_c^2)$$

Step 4: is $f_c^{[3]}(\mu_c^2)$ compatible with zero or **not**?

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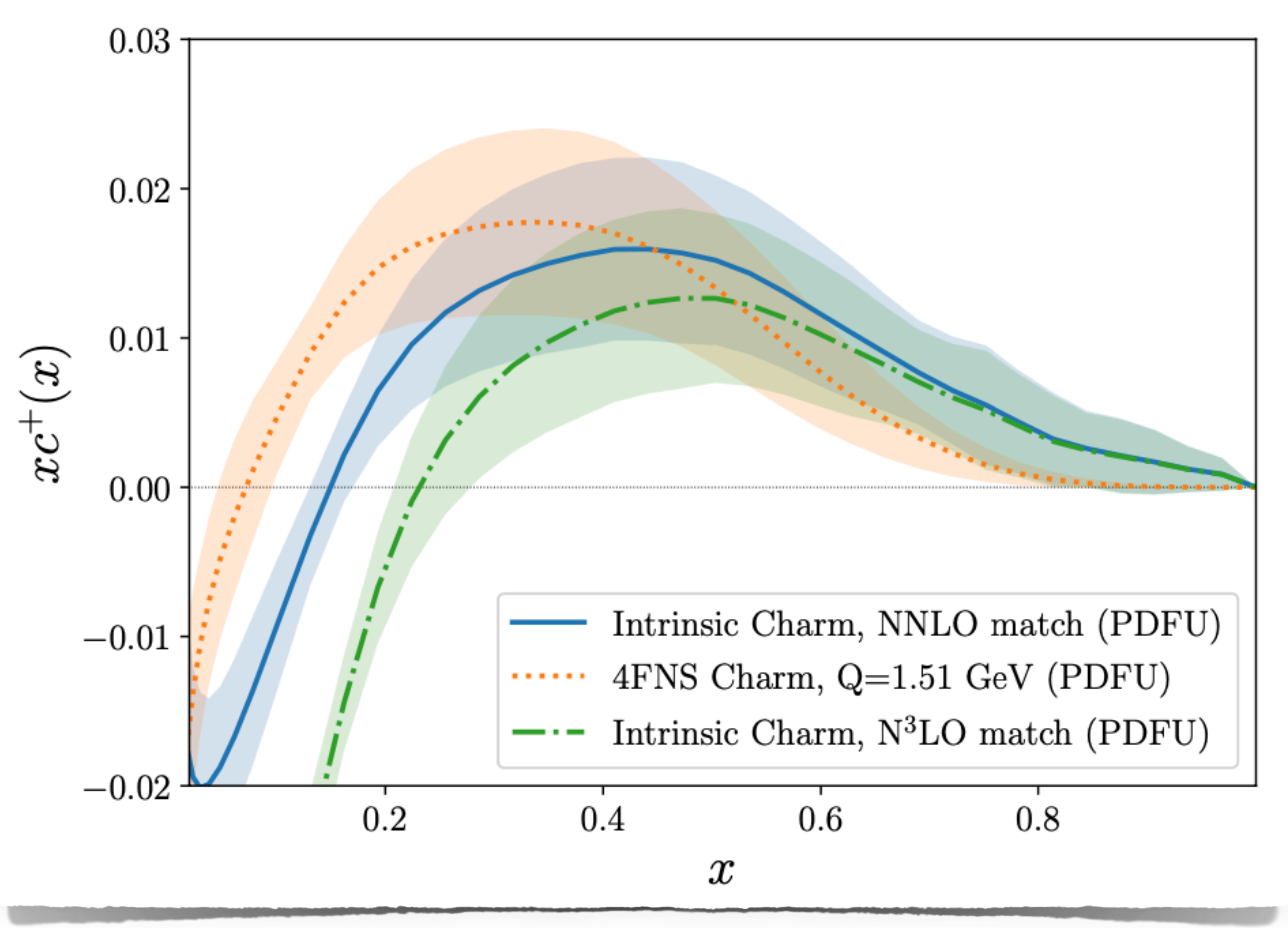
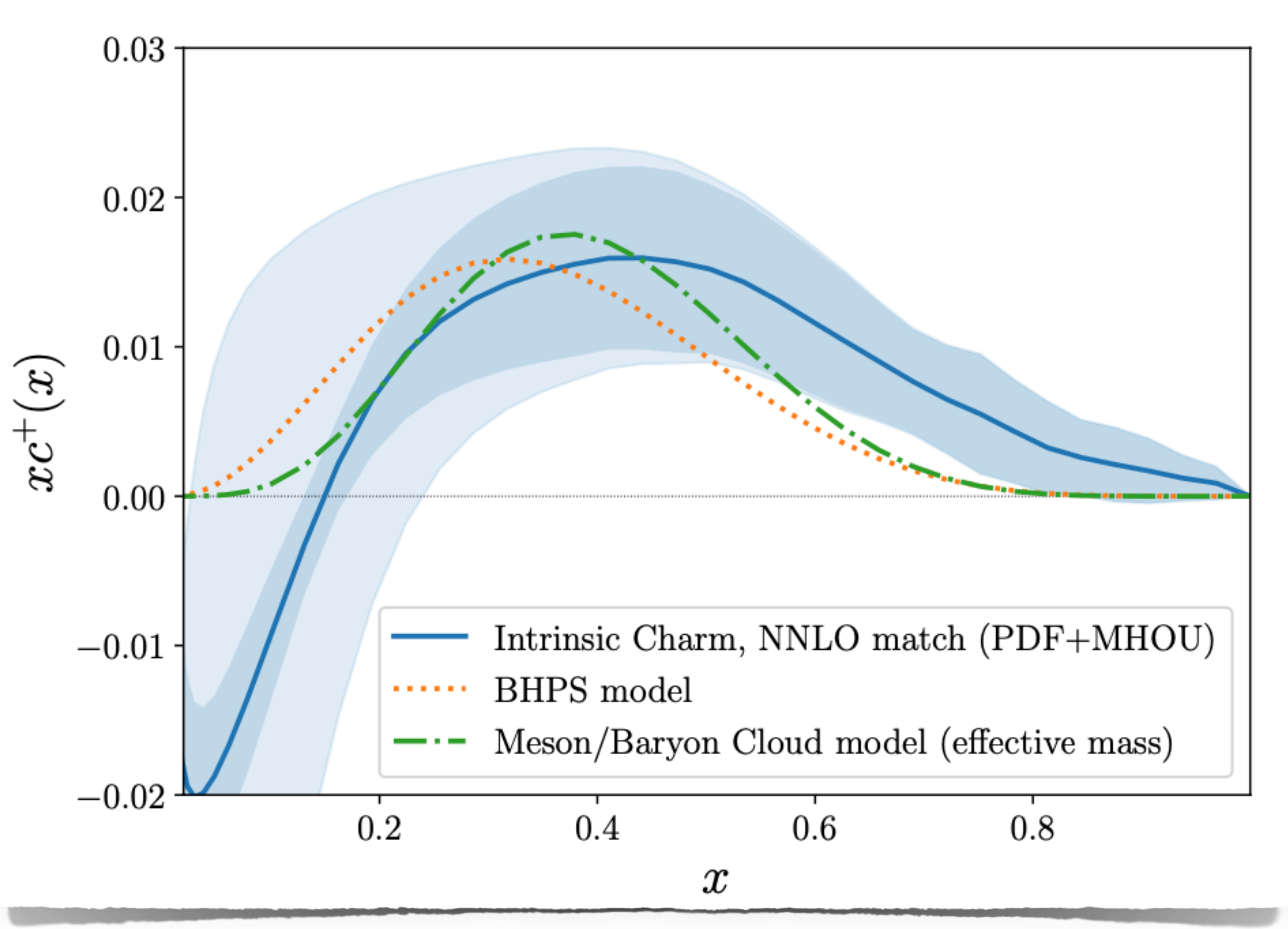
- Results of the fit: the matching is performed both at $\mathcal{O}(\alpha_s^2)$ and at $\mathcal{O}(\alpha_s^3)$
- PDFs uncertainties come from experimental uncertainties
- $c^+ = c + \bar{c} = 2c$



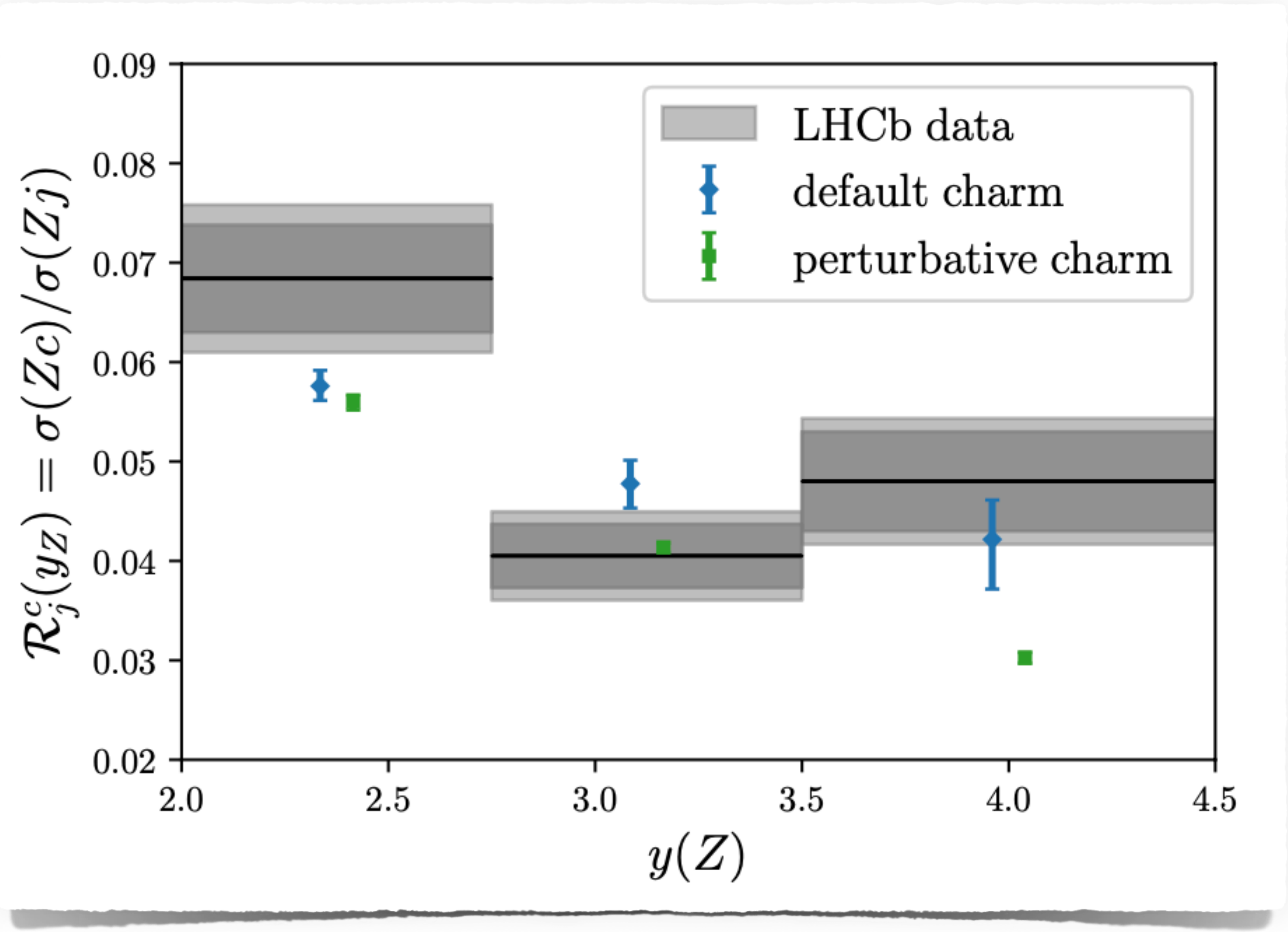

Intrinsic charm is not compatible with zero at $3\sigma$ level

- Comparison with models
- PDFs uncertainties come from experimental uncertainties + missing higher orders uncertainty




It agrees with with BHPS and Meson/Baryon models

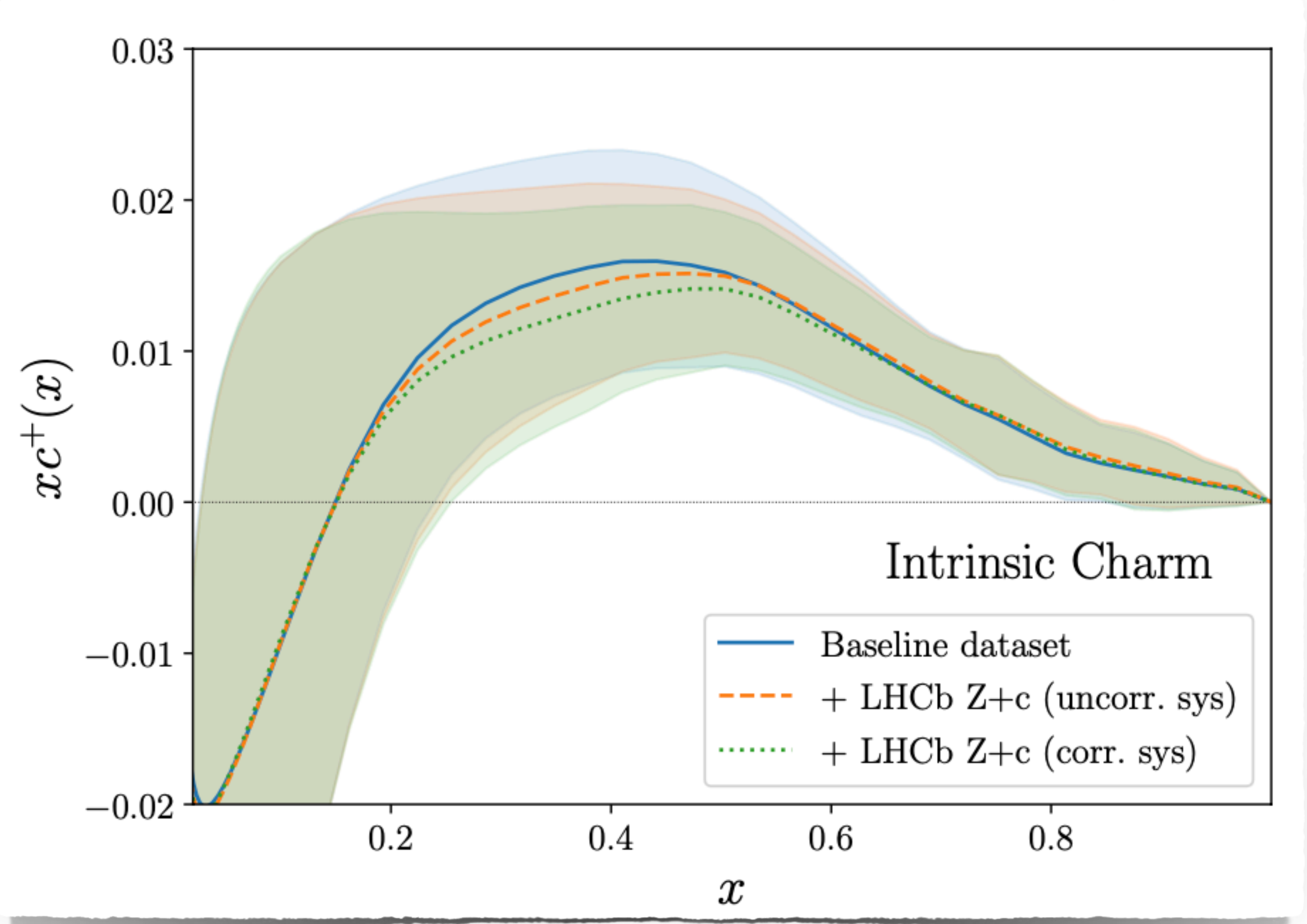
- Is our result in agreement with data not included in the fit?
- LHCb measurement of Z+c jet (sensitive to charm PDF)




Theoretical predictions agree with data!

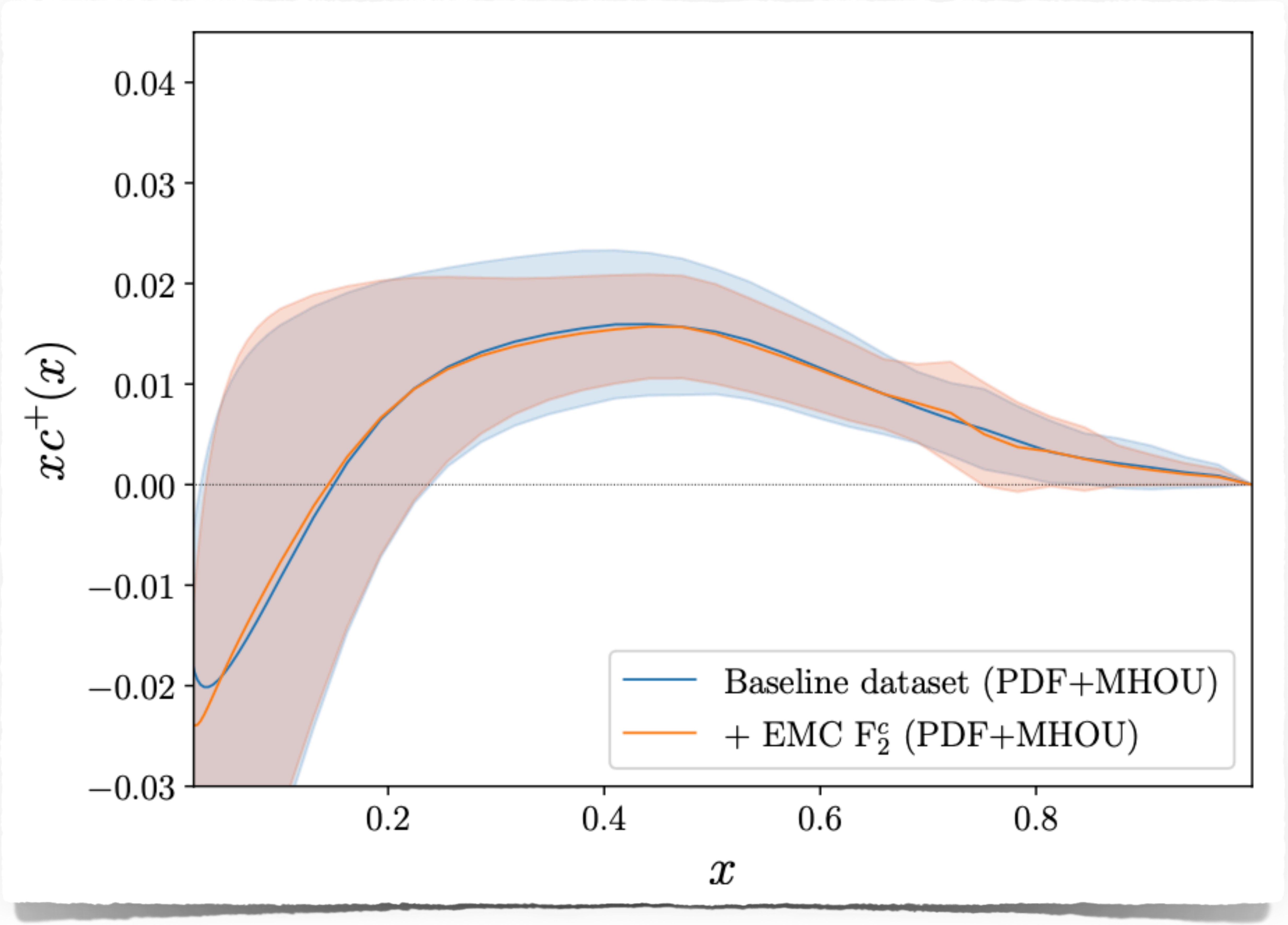
The last bin is the most correlated to the charm PDF (backup)

- Is our fit stable upon the inclusion of new data?
- LHCb measurement of Z+c jet are added to the dataset
- Two limiting cases: completely uncorrelated or fully correlated systematics between rapidity bins

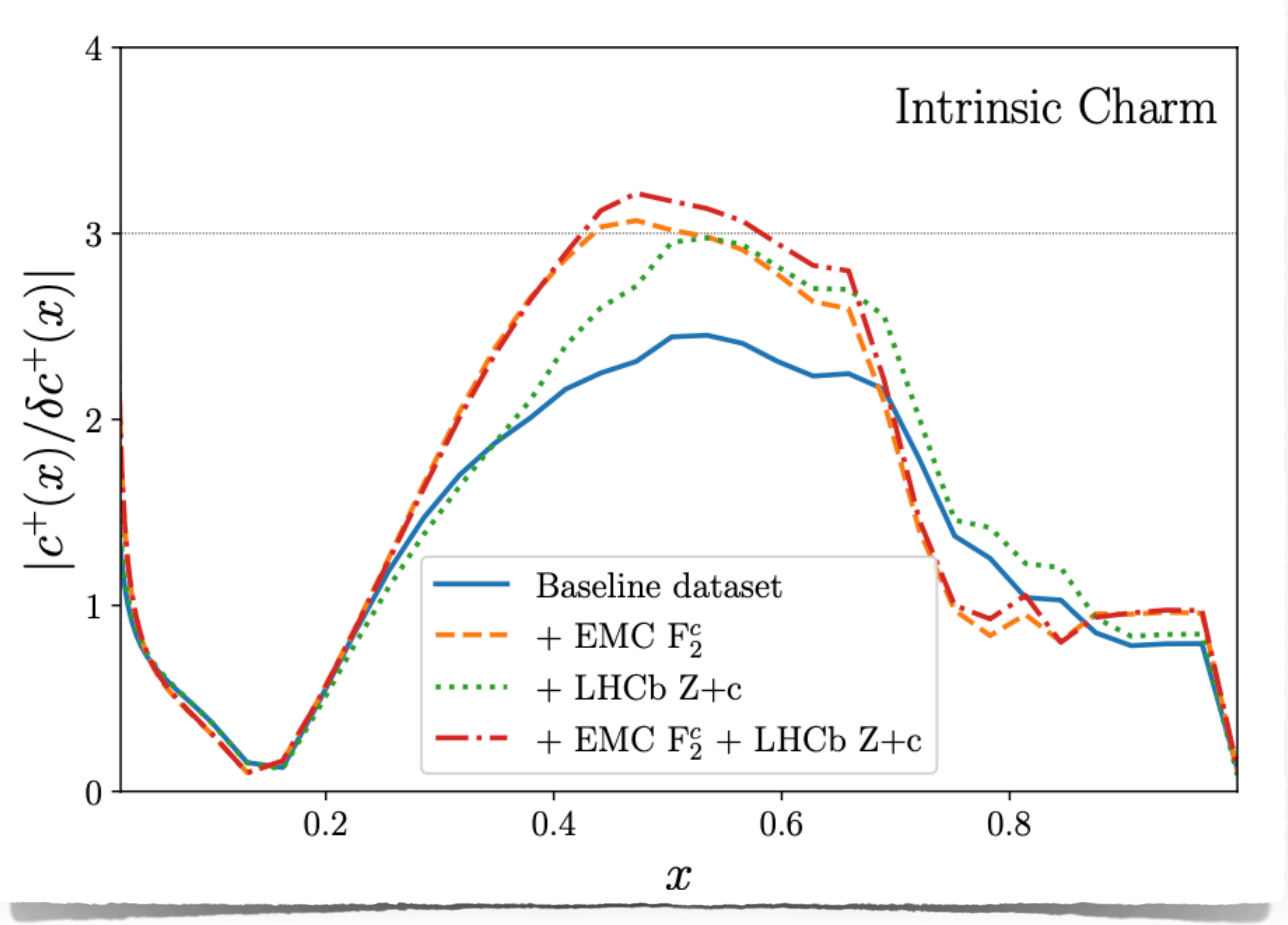



Almost same results!

- EMC DIS data with charm in the final state are added to the dataset
- They are not added to the default set since they are relatively imprecise



- Adding both LHCb and EMC data: local statistical significance




Fit is stable upon inclusion of new data!

# Outline

- What happens if we don't impose $c = \bar{c}$?

Work in progress!

In the fit we imposed $f_c^{[4]}(Q_0^2) = f_{\bar{c}}^{[4]}(Q_0^2)$

Nothing constrains $c = \bar{c}$

We extended the neural network to fit also $\bar{c}$

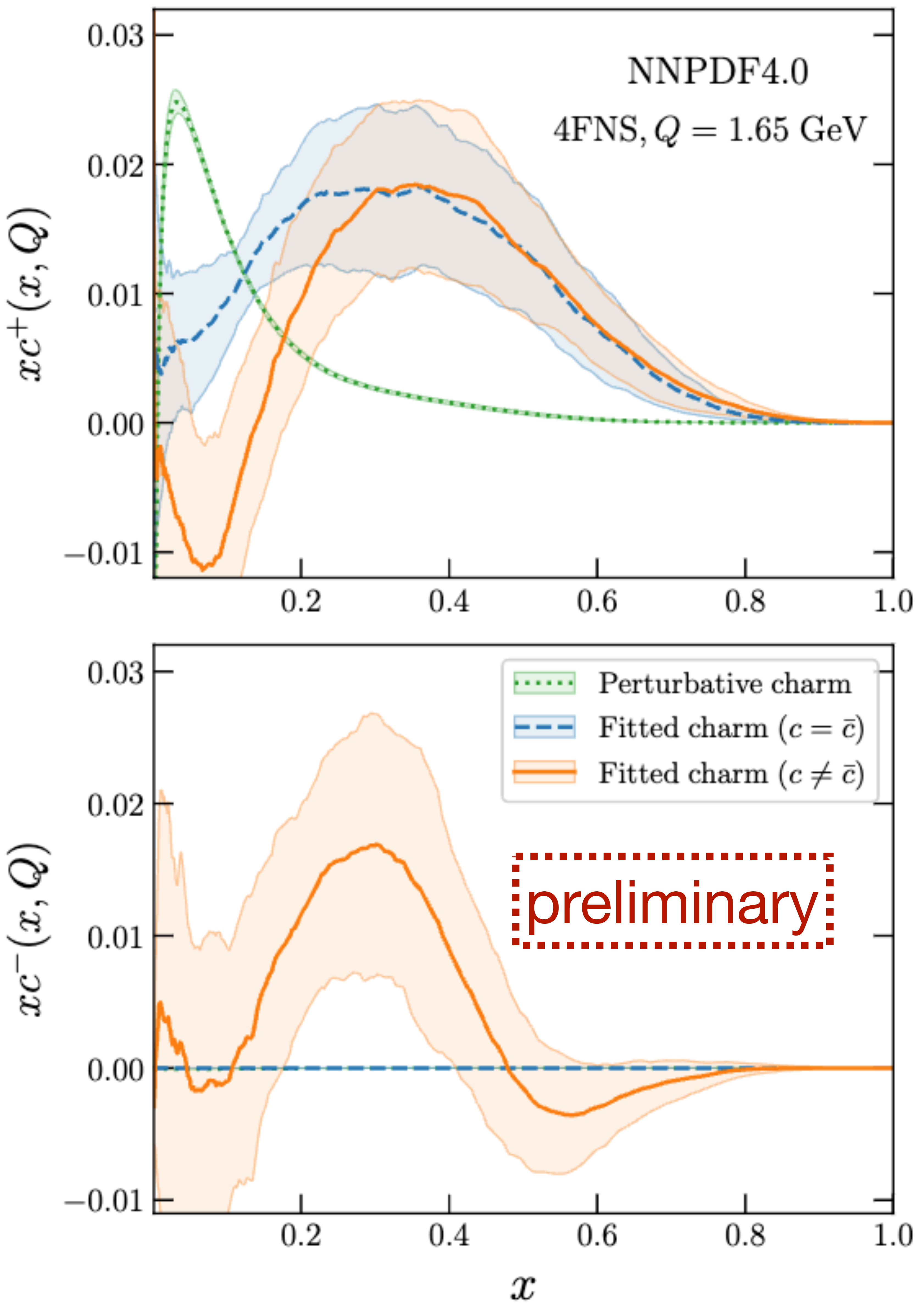
Observation: with no intrinsic charm

$$f_c^{[4]}(\mu_c) = f_{\bar{c}}^{[4]}(\mu_c) = \sum_{j=g,q,\bar{q}} A_{cj}\left(\frac{m_c^2}{\mu_c^2}\right) \otimes f_j^{[3]}(\mu_c^2)$$

**$\mathbf{c \neq \bar{c}}$ would be another evidence for intrinsic charm** **!**

- Preliminary results of intrinsic charm asymmetry
- $c^{\pm} = c \pm \bar{c}$

Work in progress!

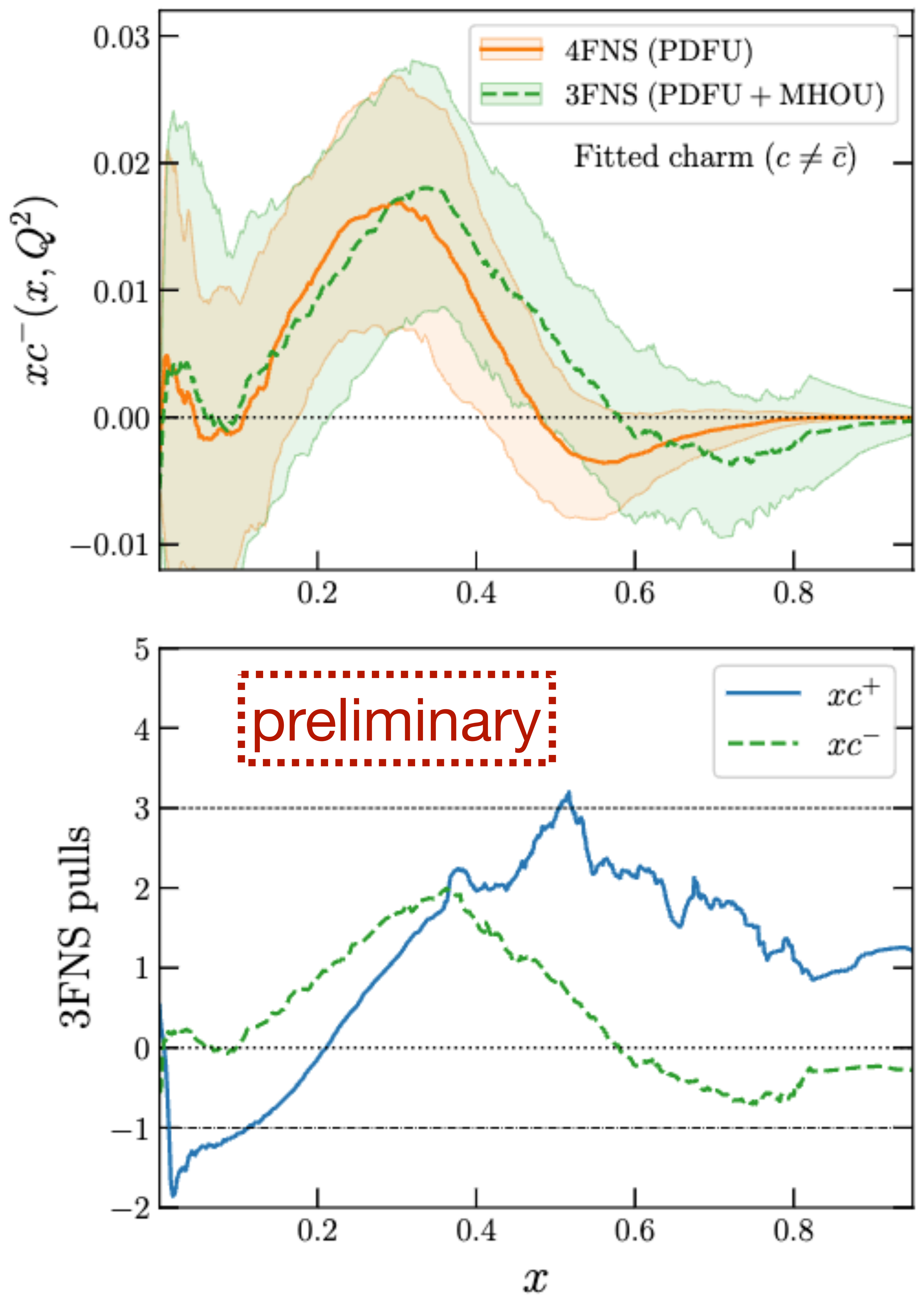



Asymmetry is observed ($c^{-} \neq 0$)

- Preliminary results of intrinsic charm asymmetry

- $$\text{pulls} = \frac{\text{central PDF}}{\text{uncertainty}}$$

Work in progress!




$2\sigma$ evidence for charm asymmetry!

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# Summary and Outlook

- ☑ Intrinsic charm is a non-perturbative component of the proton
- ☑ We disentangled the non-perturbative charm from the perturbative radiation
- ☑ We observed a non-zero intrinsic charm
- ☑ It agrees with models
- ☑ It can describe data not included in the fit
- ☑ The fit is stable upon inclusion of other data
- ☑ Investigating charm asymmetry gives $c \neq \bar{c}$

**Thank you for your attention!**

# Backup

- Neglecting the mass of the quark as soon as we cross the threshold would be a rough approximation
- How do we include mass effects?

$$
\begin{aligned}
\sigma = &+a_0 \\
&+\alpha_s\left(a_1\log(Q^2/m^2)+b_1\right) \\
&+\alpha_s^2\left(a_2\log^2(Q^2/m^2)+b_2\log(Q^2/m^2)+c_2\right) \\
&+\alpha_s^3\left(a_3\log^3(Q^2/m^2)+b_3\log^2(Q^2/m^2)+c_3\log(Q^2/m^2)+d_3\right) \\
&+\ldots
\end{aligned}
$$

$$\sigma_{\mathrm{VFNS}} = ?$$

- Neglecting the mass of the quark as soon as we cross the threshold would be a rough approximation

- How do we include mass effects?

$$
\begin{aligned}
\sigma = &+a_0 \\
&+\alpha_s \left(a_1 \log(Q^2/m^2) + b_1\right) \\
&+\alpha_s^2 \left(a_2 \log^2(Q^2/m^2) + b_2 \log(Q^2/m^2) + c_2\right) \\
&+\alpha_s^3 \left(a_3 \log^3(Q^2/m^2) + b_3 \log^2(Q^2/m^2) + c_3 \log(Q^2/m^2) + d_3\right) \\
&+\ldots
\end{aligned}
$$

rows: fixed order ⟵ 3FS

$$\sigma_{\mathrm{VFNS}} = \sigma_{\mathrm{f.o.}} + ?$$

- Neglecting the mass of the quark as soon as we cross the threshold would be a rough approximation

- How do we include mass effects?

$$
\begin{aligned}
\sigma = &+a_0 \\
&+\alpha_s \left(a_1 \log(Q^2/m^2) + b_1\right) \\
&+\alpha_s^2 \left(a_2 \log^2(Q^2/m^2) + b_2 \log(Q^2/m^2) + c_2\right) \\
&+\alpha_s^3 \left(a_3 \log^3(Q^2/m^2) + b_3 \log^2(Q^2/m^2) + c_3 \log(Q^2/m^2) + d_3\right) \\
&+\dots
\end{aligned}
$$

rows: fixed order ⟵ 3FS

columns: resummed ⟵ 4FS

$$\sigma_{\text{VFNS}} = \sigma_{\text{f.o.}} + \sigma_{\text{res}} + ?$$

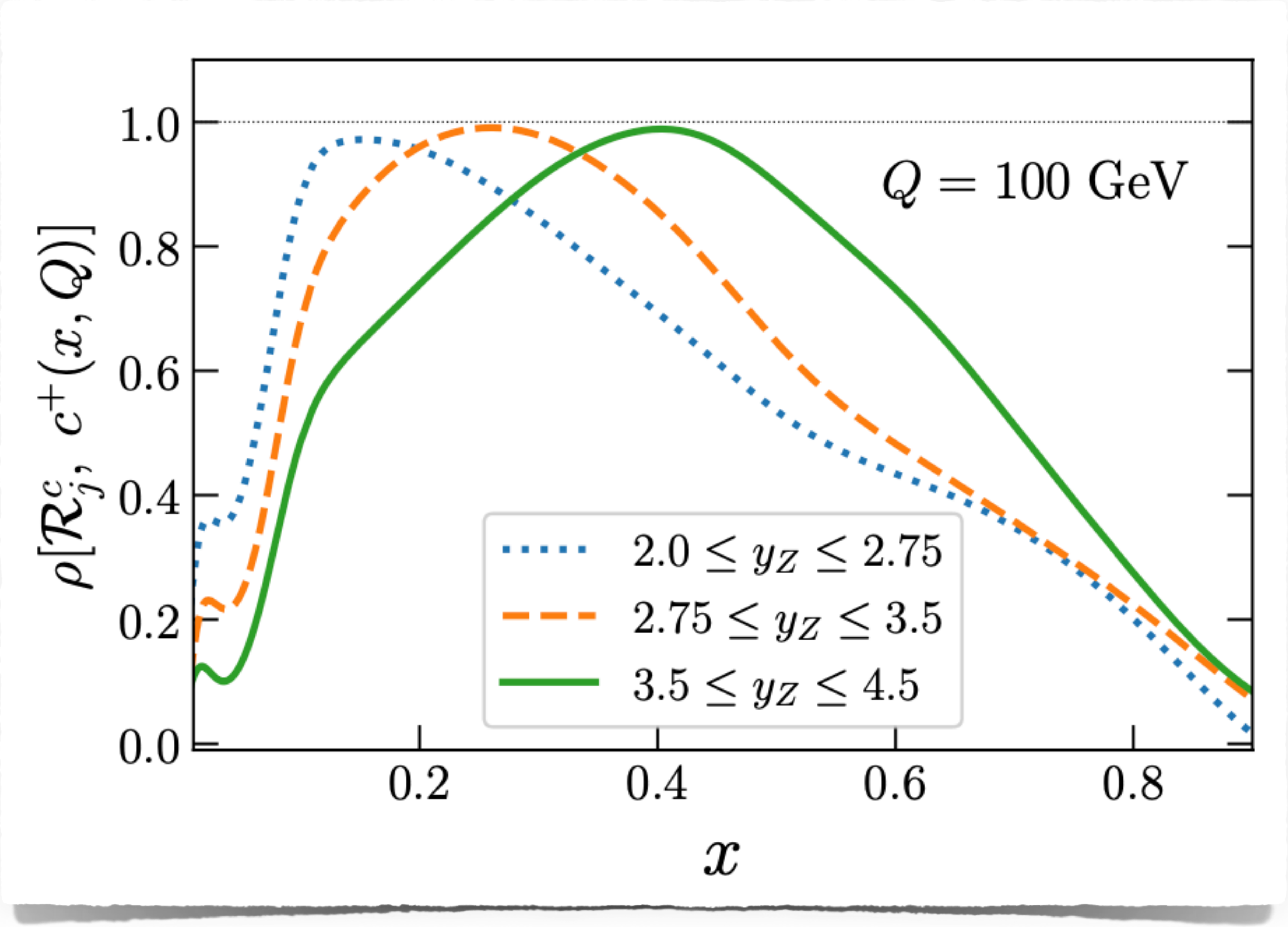
- Neglecting the mass of the quark as soon as we cross the threshold would be a rough approximation
- How do we include mass effects?

$$
\begin{aligned}
\sigma = &+a_0 \\
&+\alpha_s \left(a_1 \log(Q^2/m^2) + b_1\right) \\
&+\alpha_s^2 \left(a_2 \log^2(Q^2/m^2) + b_2 \log(Q^2/m^2) + c_2\right) \\
&+\alpha_s^3 \left(a_3 \log^3(Q^2/m^2) + b_3 \log^2(Q^2/m^2) + c_3 \log(Q^2/m^2) + d_3\right) \\
&+\ldots
\end{aligned}
$$

| | | |
|---|---|---|
| rows: fixed order | ⟵ | 3FS |
| columns: resummed | ⟵ | 4FS |
| double counting | | |

$$\sigma_{\mathrm{VFNS}} = \sigma_{\mathrm{f.o.}} + \sigma_{\mathrm{res}} - \sigma_{d.c.}$$

- Correlation coefficient between charm PDF at 100 GeV and the observable $R_j^c = \sigma(Zc)/\sigma(Zj)$




For the last curve (corresponding to the last bin of the measurements) $R_j^c$ is mostly correlated to the region of the charm peak